

SPECIFICATION

TITLE

**“MAGNETIC RESONANCE TOMOGRAPHY APPARATUS AND METHOD
EMPLOYING A TRUE FISP SEQUENCE WITH IMPROVED OFF-RESONANT
BEHAVIOR OF TWO SPIN ENSEMBLES”**

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention is directed in general to magnetic resonance tomography as employed in medicine for examining patients. The present invention is thereby specifically directed to a magnetic resonance apparatus as well as to a method for the operation thereof wherein a pulse sequence known as a true-FISP pulse sequence is employed.

Description of the Prior Art

Magnetic resonance tomography is a tomographic method for medical diagnostics that is distinguished by a high contrast resolution capability. Due to its excellent ability to present soft tissue, magnetic resonance tomography has developed into a method that is far superior to X-ray computed tomography. Magnetic resonance tomography is currently based on the application of spin echo sequences and gradient echo sequences that enable an excellent image quality given measurement times on the order of minutes.

In the presentation of the tissue of a patient, however, artifacts occur that arise from the influence of the chemical shift at the boundary layers between fat and water. A “chemical shift” is the phenomenon that the resonant frequency shifts slightly in proportion to the field strength dependent on the type of chemical bond in which the excited nucleus participates. Due to their concentration in the human body, it is mainly hydrogen nuclei of free water and fat that contribute to the image. Their relative

difference in resonant frequency amounts to about 3 ppm (parts per million). As a result thereof, a modulation of the signal intensity dependent on the echo time TE occurs given employment of steady state gradient echo sequences.

These artifacts must be avoided since they can lead to an incorrect diagnosis.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a nuclear magnetic resonance tomography apparatus and a method for the operation thereof wherein artifacts arising as a consequence of the chemical shift between a first spin ensemble, for example water, and a second spin ensemble, for example fat, are reduced or avoided.

This object is inventively achieved in a magnetic resonance tomography apparatus having a device for generating a FISP pulse sequence and for applying this sequence to a subject under examination. The pulse sequence is repeated with a repetition time T_R , with respectively different phase coding gradients and with an alternating operational sign of the flip angle α of the excitation pulse. The gradient pulse trains are thereby completely balanced, resulting in a true FISP pulse sequence.

In the inventive method and apparatus, a phase increment β is provided between successive excitation pulses in addition to the alternating operational sign of the flip angle α , so that the steady state signals for first and for second spin ensembles optionally have either the same or reversed signal polarities. Due to the incrementation of the phase by the amount β between successive excitation pulses, a precession of the magnetic moments of the first and second spin ensembles is produced in the rotating reference system. Differing from the known true FISP sequences that, for example, are set to excite water as the first spin ensemble, so that only other spin ensembles, for example fat, precess in the rotating reference system, a precession of

optionally satisfy the conditions for identical signal polarities, or for reversed signal polarities, during the repetition time T_R .

Advantageously, the phase increment β is selected such that the first and second spin ensembles simultaneously exhibit an optimally large difference angle from the respectively closest zero-axis signal crossing in the steady state signal. As a result, an efficient signal yield and a high stability of the system is assured, for example given small fluctuations of T_R .

The first spin ensemble can, for example, represent water and the second spin ensemble can represent fat.

As a result of the, free selection of the mutual signal polarities, a first dataset can be obtained on the basis of identical signal polarities and a second dataset can be obtained on the basis of reversed signal polarities.

By corresponding addition and/or subtraction of the first and second datasets, a pure image of the first or second spin ensemble can be obtained in a simple way.

DESCRIPTION OF THE DRAWINGS

Figure 1 schematically shows a nuclear magnetic resonance tomography apparatus operable in accordance with the invention.

Figure 2 shows a true FISP pulse sequence (FISP sequence with completely balanced gradient pulse trains) with a phase increment $\Delta\phi=\beta$ as employed according to the invention.

Figure 3a explains the phase increment $\Delta\phi=\beta$ by projection of the spin of a spin ensemble into the rotating reference plane x-y, whereby the RF signal is in-phase.

Figure 3b explains the phase increment $\Delta\phi=\beta$ by projection of the spin of a spin ensemble into the rotating reference plane x-y, whereby the RF signal is opposed phase.

Figure 4 shows the SSFP signal given off-resonance dependent on the chemical frequency shift Δf .

Figures 5a through 5c and Figures 6a through 6d show the steady state signal dependent on the off-resonance angle taking a number of different cases into consideration.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 is a schematic illustration of a magnetic resonance tomography apparatus for generating a magnetic resonance image of a subject according to the present invention. The basic components of the magnetic resonance tomography apparatus correspond to that of a conventional tomography apparatus. A basic field magnet 1 generates a temporally constant, strong magnetic field for polarizing and thereby aligning nuclear spins in the examination region of a subject such as, for example, an examined part of a human body. The high homogeneity of the basic magnetic field required for the magnetic resonance measurement is defined in a spherical measurement volume M into which the parts of the human body to be examined are introduced. For assisting in satisfying the homogeneity requirements and, in particular, for eliminating time-invariable influences, shim plates of ferromagnetic material are attached at suitable locations. Time-variable influences are eliminated with shim coils 2 that are driven by a shim coil power supply 15.

A cylindrical gradient coil system 3 that is composed of three windings (coils) is introduced into the basic field magnet 1. An amplifier 14 supplies each winding with current for generating respective linear gradient fields in the directions of a Cartesian

coordinate system. The first winding of the gradient field system 3 generates a gradient G_x in the x-direction, the second winding generates a gradient G_y in the y-direction and the third winding generates a gradient G_z in the z-direction. Each amplifier 14 includes a digital-to-analog converter DAC that is driven by a sequence controller 18 for the generation of gradient pulses at the correct times.

A radio-frequency antenna 4 is located within the gradient field system 3, this antenna 4 converting the radio-frequency pulses supplied by a radio-frequency power amplifier 30 into a magnetic alternating field for excitation of the nuclei and alignment of the nuclear spins of the examined subject, or of the examined region of the subject. The radio-frequency antenna 4 also receives the alternating field emanating from the precessing nuclear spins, i.e. the nuclear magnetic resonance echo signals usually produced by a pulse sequence composed of one or more radio-frequency pulses and one or more gradient pulses, and the received signals are supplied as a voltage to an amplifier 7 and from there to a radio-frequency reception channel 8 of a radio-frequency system 22. The radio-frequency system 22 also has a transmission channel 9 in which the radio-frequency pulses for the excitation of the nuclear magnetic resonance are generated. The respective radio-frequency pulses are digitally presented in the sequence controller 18 as a sequence of complex numbers on the basis of a pulse sequence prescribed by the system computer 20. From an input 12, this numerical sequence is supplied as a real part and an imaginary part to a digital-to-analog converter DAC in the radio-frequency system 22 and is supplied from the latter to a transmission channel 9. In the transmission channel 9, the pulses sequences are modulated onto a radio-frequency carrier signal having a base frequency that

corresponds to the resonant frequency of the nuclear spins in the measurement volume.

Switching from the transmission mode to the reception mode ensues via a transmission-reception diplexer 6. The radio-frequency antenna 4 radiates the radio-frequency pulses for excitation of the nuclear spins into the measurement volume M and samples resulting echo signals. The acquired nuclear magnetic resonance signals are demodulated in phase-sensitive fashion in the reception channel 8 of the radio-frequency system 22 and are converted via the analog-to-digital converter DAC into a real part and an imaginary part of the measured signal. An image computer 17 reconstructs an image from the measured data acquired in this way. Administration of the measured data, the image data, and the control programs ensues via the system computer 20. The sequence controller 18 controls the generation of the respectively desired pulse sequences and the corresponding sampling of k-space on the basis of control programs. In particular, the sequence controller 18 controls the switching of the gradients at the correct time, the transmission of the radio-frequency pulses with defined phase and amplitude as well as the reception of the nuclear magnetic resonance signals. The timing signals for the radio-frequency system 22 and the sequence controller 18 are made available by a synthesizer 19. The selection of corresponding control programs for generating a magnetic resonance image ensues via a terminal 21 that has a keyboard as well as one or more picture screens.

According to the present invention, the magnetic resonance tomography apparatus is operated with a true FISP pulse sequence.

Figure 2 shows such a true FISP sequence. FISP stands for "fast imaging with steady precession" and is a specific form of the gradient echo sequence.

As in conventional imaging sequences, a rephasing with respect to a slice selection gradient G_s and a pre-dephasing with respect to a readout gradient also occurs here. The dephasing of the transverse magnetization produced by the gradients is compensated by this gradient switching, so that an echo signal arises, referred to as a gradient echo. The basic idea, thus, is that the transverse magnetization is restored after the signal readout and can be used for the next sequence execution.

The echo signal is generated exclusively by gradient reversal.

The repetition time T_R is the time after which one RF excitation pulse follows another. The echo signal ensues after the time $T_E = \frac{T_R}{2}$ and can be acquired with the readout gradient G_R .

The true FISP signal is distinguished by a complete symmetry in the time domain, i.e. the gradient pulse trains are completely balanced. All magnetization components are again refocused as a result of the complete symmetry of the gradient pulse trains in the time domain, so that the ideal steady state signal arises after a short transiency.

For phase coding, a gradient field is activated for a fixed time before the acquisition of the steady state signal and after the acquisition, the strength of this gradient field being decreased or increased in steps by the amount ΔG_R in successive sequence executions.

The true FISP sequence makes high demands on the calibration of the hardware and software because a misadjustment leads to unacceptable interference stripes in the image.

The RF pulses have an operation sign of the flip angle which alternates from pulse-to-pulse α . In addition to the alternating operational sign of the flip angle α , a

phase increment $\Delta\phi=\beta$ is also generated, i.e. a difference in the phase of two successive RF pulses is produced. In other words, the phase of a following RF pulse is respectively raised by the value β compared to the preceding pulse. This phase increment $\Delta\phi$ with the magnitude β produces a precession of the water spins in the rotating reference system, in addition to the precession of the fat spins.

It should be noted that the repetition time T_R , the readout time T_E and the rest of the system are usually matched to water in a true FISP pulse sequence, as shown for example, in Figure 2, so that the water spins do not precess in the rotating reference system, i.e. they are "on-resonance". The precession angle β_W of water is zero, $\beta_W = 0$. All other spin ensembles such as, for example, the second strongest spin ensemble, fat, precess in the rotating reference system. The spin ensemble, fat, precesses by the angle β_F during the repetition time.

Due to the use of the aforementioned phase increment $\Delta\phi=\beta$ between successive RF pulses, a precession of the water spins in the rotating reference system also is accomplished. The mechanism is explained more precisely with reference to Figure 3a and 3b. As the two spin ensembles providing the strongest signal, the water spins and the fat spins precess with different velocities. During the repetition time T_R , i.e. between two readout times, the fat spins precess by an angle β_F and the water spins precess by an angle β_W . These precession angles β_F and β_W can be varied by a corresponding setting and selection of the value β of the phase increment $\Delta\beta$, so that the respective signal polarity of the steady state signals of water and fat can be individually set. For example, a first value of β is selected such that the resulting steady state signals of water and fat have the same signal polarities, whereupon another value of β is selected at which the steady state signals of water and fat exhibit opposite signal

polarities. As a result, it is possible to filter out a pure steady state signal of water or fat by suitable addition and subtraction calculating steps and correspondingly display it. An exclusive presentation of the water spin ensemble or of the fat spin ensemble thus can be obtained in a simple way.

Figures 3a and 3b explain the relationship between the precession angle, for example β_W or β_F , of a spin ensemble and the resulting RF and steady state signals. Figures 3a and 3b show the projection of a spin of a spin ensemble into the rotating reference plane x-y. The spin of the spin ensemble traverses a precession angle β_F in the repetition time T_R . More detailed explanations with reference to the angle of the precession angle β_F of the spin ensemble, fat, are presented below with reference to Figures 3a and 3b. The explanations apply, of course, only for spins that precess in the rotating reference system, i.e. that are "off-resonant". Spins referred to as "on-resonant" spins do not precess in the rotating reference system but are folded back and forth on the x-axis by the RF signal with an alternating flip angle α . This, for example, is the case for water spins in the aforementioned system wherein the overall system is adapted to the resonance of the water spins, so that these do not precess in the rotating reference system. The case of precession of the spins in the rotating reference system, referred to as "off-resonant" spins, that applies for the present invention is shown in Figures 3a and 3b.

In Figure 3a, the precession angle β_F satisfies the mathematical condition

$$\left| \frac{\beta_F}{2} \right| < 90^\circ$$

Since a spin precesses by the angle β_F during T_R , the spin is read out in phase with the RF signal in this case. This means that, following an RF pulse with positive operational sign ($+\alpha$), the signal (steady state signal) that is read out likewise has a positive operational sign. Figure 3a shows an example.

When a spin is initially located in the second quadrant of the rotating reference system, then the RF signal $+\alpha$ mirrors or folds it into the first quadrant. During the time in which no RF signal is present, i.e. in the repetition time T_R , the spin precesses by the angle β_F into the fourth quadrant of the rotating reference system. When crossing the x-axis at $T_E = \frac{T_R}{2}$ after covering the angle $\frac{\beta_F}{2}$, the signal is read out with positive operational sign. After the time T_R , the spin, which is now located in the fourth quadrant of the rotating reference system, is mirrored into the third quadrant by the following RF signal α . After the time $T_E = \frac{T_R}{2}$, the spin again crosses the x-axis; the signal is read out with a negative operational sign. The spin is again situated at its original position after a further time $\frac{T_R}{2}$, so that the operation begins anew.

The signal polarity is positive given the explained "in-phase" case, i.e. $\left| \frac{\beta_F}{2} \right| < 90^\circ$. This is because the spin vector crosses the positive x-axis after a positive RF pulse. A positive RF signal corresponds to a positive steady state signal. When the spin vector is in the fourth quadrant and is folded into the third quadrant by an RF signal, then it crosses the negative x-axis after the time $\frac{T_R}{2}$, so that a negative steady state signal arises. Negative RF pulse corresponds to a negative steady state signal.

In Figure 3b, the spin signal that is read out (steady state signal) is "opposed phase" with respect to the RF signal. Here, the precession angle β_F satisfies the mathematical condition

$$90^\circ < \left| \frac{\beta_F}{2} \right| < 270^\circ,$$

i.e. the precession angle β_F that the spin covers in the time T_R is greater than 180° . In contrast to Figure 3a, the signal polarity is negative. When a spin is located in the second quadrant of the rotating reference system and when it is subsequently mirrored into the first quadrant of the rotating reference system by a positive Rf signal, then it subsequently precesses into the fourth quadrant and thereby crosses the negative x-axis after the time $T_E = \frac{T_R}{2}$. Although the RF signal was positive, a negative steady state signal results therefrom. The spin is subsequently folded into the third quadrant by a negative RF signal and precesses into the second quadrant in the time T_R . This time, the steady state signal is positive since it crosses over the positive part of the x-axis after the time $\frac{T_R}{2}$.

It can be clearly seen both in Figure 3a as well as in Figure 3b that the spin is not folded or flipped by a following RF pulse, and thus no steady state signal can be obtained in the specific instance $\left| \frac{\beta_F}{2} \right| = 90^\circ$, i.e. when the spin precesses by 180° during the time T_R . In this case, the steady state signal has a zero-axis crossing.

It should be noted that Figures 3a and 3b and the corresponding explanations respectively refer to the spin or the total magnetic moment of a spin ensemble. The signal obtained upon readout in the magnetic resonance tomography apparatus thus is the combination of the steady state signals of the spins of a number of spin ensembles, such as, for example, of the two spin ensembles, water and fat. The values β_W and β_F by which the first spin ensemble, water, and the second spin ensemble, fat, respectively precesses in the rotating reference system during the repetition time T_R are

directly defined by appropriate selection and setting of the value β of the phase increment $\Delta\beta$. The value β_F by which the second spin ensemble, fat, precesses in the rotating reference system during the repetition time T_R is dependent on the repetition time T_R and β_W according to the following equation:

$$360^\circ * \Delta f * T_R = \beta_F - \beta_W.$$

The chemical frequency shift Δf between fat and water given, for example, a magnetic field $B_0 = 1.5$ T amounts to approximately 220 Hz.

Water does not precess without phase increment $\Delta\phi=0$, so that $\beta_W = 0$ applies. Given activation of a phase increment β , water precesses in the rotating reference system with $\beta_W = -\beta$, whereby the precession angle β_F of fat changes according to the above equation.

In order to assure an optimally good stability of the system and in order to obtain a high signal yield, it is important that the value β is selected such for a preset T_R that fat and water simultaneously respectively have an optimally great difference angle from the respectively closest zero-axis signal crossing of the steady state signal. Since water as well as fat precess in the rotating reference system, T_R need not be exactly adjusted in order to keep the system stable.

Figure 4 shows the SSFP signal (resonance signal) of a spin ensemble (for example, fat) given off-resonance dependent on $\frac{\beta_F}{T_R * 360^\circ}$.

Given an arbitrarily selected repetition time T_R , the steady state signal has a real, positive signal at the readout time $T_E = \frac{T_R}{2}$ given spins that precess by less than

approximately $\pm 180^\circ \left(\pm \frac{1}{2T_R} \right)$ per T_R . Precession angles of $\pm 180^\circ$ through $\pm 540^\circ$ $\left(\pm \frac{1}{2T_R} \text{ through } \pm \frac{3}{2T_R} \right)$ yield real signals with negative polarity, etc. Given $180^\circ + k*360^\circ$

precession, the steady state signal amplitude has a zero-axis crossing. Values for zero-axis signal crossings are, for example $-\frac{3}{2T_R}$, $-\frac{1}{2T_R}$, $+\frac{1}{2T_R}$, $+\frac{3}{2T_R}$, ...

As mentioned above, the value β of the phase increment $\Delta\phi$ should be set such that the precession angles β_F and β_W of fat or water do not lie in the proximity of a signal zero-axis crossing in the respective resonance signal and each have an optimally great difference angle therefrom. For example, such a case would be:

$$\beta_W = -90^\circ$$

$$\beta_F = +90^\circ$$

The RF signals are in-phase (see Figure 3a) for both spin collectives, which leads to the same signal polarities for water and fat.

An example of unequal signal polarities would be:

$$\beta_W = +90^\circ$$

$$\beta_F = +270^\circ$$

Here, the resonance signal for fat lies in the negative real range. The corresponding RF signal is opposed phase. With the positive resonance signal of water, this leads to a combination of unequal signal polarities in the measured overall resonance signal.

Figures 5a through 5c, and 6a through 6d are intended to more specifically explain the two instances $\left|\frac{\beta_{F,W}}{2}\right| < 90^\circ$ and $90^\circ < \left|\frac{\beta_{F,W}}{2}\right| < 270^\circ$, and thus the free selection possibility between identical and unequal signal polarities of the resonance signals of fat and water dependent on impressing a phase increment $\Delta\phi=\beta$ between the successive RF pulses.

In the case of Figure 5a, water is on resonant, i.e. the water has no precession whatsoever ($\beta_W=0$) in the rotating reference system. The fat is off resonant and has the precession angle β_F . The respective signals of water and fat have the same operational

sign, both have a positive steady state signal, so that a correspondingly large value arises in the measured overall resonance signal.

According to Figure 5b, the phase increment $\Delta\phi=\beta$ is inventively selected with a given T_R so that the precession angles β_W and β_F of water or fat come to lie symmetrically around the phase 0° . The condition for this is:

$$\beta = 180^\circ * \Delta f * T_R = \frac{\beta_F - \beta_W}{2}$$

The zero point thus is placed exactly in the middle between water and fat. As a result, water and fat are respectively displaced to new precession angles of $\beta'_W = -\beta$, $\beta'_F = +\beta$. Both precession angles have the same distance from the respective signal zero-axis crossing.

In Figure 5c, $\Delta\phi=\beta$ is inventively selected with a given T_R so that the precession angles of water and fat come to lie symmetrically around the phase 180° . To this end, the phase increment β in the case of Figure 5b is increased by 180° , i.e. $\beta \rightarrow \beta + 180^\circ$. The condition for this is $\beta = 180^\circ * \Delta f * T_R - 180^\circ = \frac{\beta_F - \beta_W}{2} - 180^\circ$. The fat thus comes to lie under the negative part, the water under the positive part of the steady state signal. This leads to a reversed polarity of the respective resonance signals. Both new precession angles $\beta'_W = 180^\circ - \frac{\beta_F - \beta_W}{2}$ and $\beta'_F = 180^\circ + \frac{\beta_F - \beta_W}{2}$ are again equidistant from the signal zero-axis crossing at 180° . Moreover, "equidistant" means that they are maximally insensitive to, for example, field inhomogeneities.

The case of $|\beta_F - \beta_W|$ lying between 180° and 540° is shown in Figure 6a. The fat has a negative signal when water is on resonant ($\beta_W=0$).

In this second case, both instances, namely that fat and water yield identical or reversed operational signs, again can be achieved by a suitable selection of β . However, there are two case distinctions, Figure 6b and Figure 6c, for the case of

identical polarity. When $|\beta_F - \beta_W|$ lies between 180° and 360° , fat and water both have a positive signal. When $|\beta_F - \beta_W|$ stems from the range $[360^\circ; 540^\circ]$, fat and water lie in different positive signal curves. In both instances, fat and water have the same positive polarity. The conditions for this are:

$$\beta = 180^\circ * \Delta f * T_R \quad (\text{Figure 6b})$$

i.e. β'_W and β'_F are symmetrical around the phase 0° , and

$$\beta = 180^\circ * \Delta f * T_R - 360^\circ \quad (\text{Figure 6c})$$

i.e. β'_W and β'_F are symmetrical around the phase 360° .

For the case of reversed polarity, shown in Figure 6d, β again can be selected such that fat and water come to lie symmetrically around the phase 180° . The water signal is positive and the fat signal is negative. Opposite polarity is present given equidistant signal zero-axis crossings.

Although modifications and changes may be suggested by those skilled in the art, it is the intention of the inventor to embody within the patent warranted hereon all changes and modifications as reasonably and properly come within the scope of his contribution to the art.